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LATE STAGES IN THE EVOLUTION OF CLASSICAL NOVAE*

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ABSTRACT

We have begun a study of the long term evolution of novae in outburst in order to determine the means by which they return to quiescence when nuclear burning has ended. This project involves both IUE and optical observations and theoretical predictions. Recently, in the initial observational part of this project, we have obtained IUE SWP spectra of GQ Mus 1983 and QU Vul 1984. Each spectrum was a 16 hour exposure using a combined US1 plus Vilspa shift. No novae have been studied in the UV for as long as QU Vul and GQ Mus and observations of their spectral evolution are providing unique data on the turn-off time scale. We have also obtained the spectra of old novae from the IUE archives in order to compare and contrast the existing spectra with those of GQ Mus and QU Vul. The theoretical prediction is that a nova should be very hot just before turnoff but X-ray observations from EXOSAT do not confirm this prediction.

I. INTRODUCTION

Novae occur in cataclysmic binary systems in which a Roche lobe filling secondary is losing hydrogen-rich material through the inner Lagrangian point onto a white dwarf primary. Theoretical studies show that the accumulating shell of hydrogen on the white dwarf is unstable to a thermonuclear runaway and simulations of this phenomena reproduce many of the observed features of a nova explosion (Gallagher and Starrfield 1978; Starrfield 1986, 1989). The calculations further imply that the energetics of the outburst, and thus the type of nova, is sensitive not only to the abundances of the intermediate mass elements, but also to the mass of the accreted shell, white dwarf mass, and accretion rate (Starrfield 1989).

These same calculations show that not all of the accreted material is ejected during the explosive phase of the outburst but that a significant fraction can remain on the white dwarf after the initial explosion and radiate at near constant luminosity for months to years. The existence of a hot, luminous, remnant has been confirmed, in part, by UV studies done with the IUE Satellite and with X-ray studies of EXOSAT.

The theoretical calculations predict that the hydrostatic remnant has a radius that greatly exceeds that of a cool white dwarf. Since part of the luminosity of the remnant is produced by continuing nuclear burning in the shell source at the bottom of the accreted layer, it is radiating at a value that is determined by the mass of the white dwarf core (Paczynski 1971). For very massive white dwarfs, this luminosity can approach the Eddington luminosity. We point out, however, that the envelope mass is now much less than

$10^{-4}M_{\odot}$ and the radius is much smaller than a solar radius. Therefore, most of the energy will be emitted at UV, EUV, or soft X-ray wavelengths. The calculations predict that the final turn-off will be very rapid (Starrfield *et al.* 1990a) but there have been no ultraviolet observations done to test this prediction.

Because the luminosity is close to Eddington, mass should be driven off of the extended surface of the white dwarf at some rate. In addition, mass loss must occur in order for the nova to return to quiescence and evolve to another outburst since the time scale for nuclear burning of the envelope is hundreds of years. Nevertheless, it is still not certain what drives this mass loss. Nevertheless, the radius of the remnant must shrink after optical maximum which will cause the effective temperature of the remnant to grow to values exceeding 10^5K . For the most massive white dwarfs, the effective temperature could reach values exceeding $5 \times 10^5\text{K}$ (Starrfield 1990a,b).

However, EXOSAT data suggested that the remnants in four novae (GQ Mus 1983, PW Vul 1984, QU Vul 1984, and RS Oph 1985) were considerably cooler than predicted for the final stages of outburst (Ögelman, Krautter, and Beuermann 1987). While the four novae were observed at different stages of their outbursts, the temperature measured for each nova was about $3 \times 10^5\text{K}$. This temperature was too low for GQ Mus and RS Oph, observed late in their outbursts, and too high for PW Vul and QU Vul which were observed early in their outbursts. The cause of this discrepancy remains a puzzle and one that we are trying to solve with this study of old novae.

II. IUE OBSERVATIONS

In order to understand how novae eject the entire accreted envelope and return to quiescence, we have continued to obtain spectra of a few novae throughout their outburst. In addition, we have also searched the IUE archives and obtained the spectra of all of the old novae that exist in the archives. We are grateful to Cassatella *et al.* (1990) for pointing out some these images. In the next few paragraphs, we present some of these spectra and discuss each nova in turn. A list of each of the novae, their year of outburst, present magnitude (Duerbeck 1987), A_v (Harrison and Gehrz 1988), and the image number and date of the last SWP spectrum are given in Table 1. It turns out that virtually all of the bright novae, which have appeared in the last hundred years, can be found in the IUE Archives. The novae that are missing are too reddened to obtain a useful spectrum in a combined US1 plus Vilspa shift. We will not display all of the old novae in this paper, only those that provide a range of dates since the optical outburst. We also do not display the images of recurrent novae that exist in the archives (see Shore *et al.* 1990; these proceedings).

1) CK Vul (1670) is the oldest nova with a recorded outburst and was recovered by Shara and Moffett (1982). Although its outburst characteristics are poorly known, it was definitely a nova and ejected a shell. It was detected by IUE but the spectrum (Figure 1) is underexposed and it will take a combined shift (US1 plus Vilspa) to obtain good S/N for the continuum and measurable strengths for the emission lines. It appears that NIII] 1750Å is present as is [OIII] 1660Å, 1666Å. It is futile to try and identify more lines without a better exposure.

2) V841 Oph (1841) was a slow nova and it is still quite bright (Humason 1938). One IUE spectrum was obtained in 1980 (Figure 2) but it has too many defects to be usable (those are hits at 1640Å and 1550Å). Inasmuch as this is the oldest recovered nova from the 1800's and it is still luminous at minimum, we suggest that further IUE data be obtained.

3) Q Cyg (1876) was quite fast and its light curve resembled that of CP Pup which was one of the fastest novae on record. Humason (1938) found a blue continuum. The IUE spectrum was obtained in 1989 (Figure 3) and it is well exposed. There are a large number of emission lines present in this spectrum and it would be useful to obtain another SWP spectrum in order to confirm the reality of some of the weaker features. CIII] 1909Å and [OIII] 1660Å, 1666Å are definitely present and NIV] 1486Å is probably present. This old nova seems rather active for an outburst that occurred 113 years prior to this spectrum.

4) T Aur (1891) was the first nova in which spectra were obtained during the outburst. It also has a measured orbital period of .204 days. The light curve during the outburst strongly resembled that of DQ Her (1934) and the deep transition and recovery in the light curve showed that this nova also formed dust. The existing IUE spectrum was obtained in 1983 and it is very underexposed (Figure 4). One cannot be sure of the reality of any of the emission line features. If we assume that we have detected a usable continuum, then a spectrum about 3 times longer will have useful S/N. This should be possible with a combined US1 plus Vilspa shift.

5) DI Lac (1910) was a moderate speed nova which has a measured orbital period of 0.544 days. It is still bright in the UV (Figure 5) with a steep blue continuum and a spectrum that resembles that of V841 Oph. CIV shows a P-Cygni feature and both 1640Å and 1660Å,

1666Å are present. It also appears that NV 1240 is present which suggests that the underlying object could still be hot. Some of the other features are probably hits. This is another object that warrants additional ultraviolet data.

6) **BT Mon (1939)** rose from below 17th mag and *has not declined to its pre-outburst brightness*. It is a well studied old nova and has a measured orbital period of 0.333 days. The IUE spectrum (Figure 6) is flawed by hits at CIV and just blueward of CIV. He II 1640Å and OIII] 1660Å, 1666Å are present and strong and it is possible that this nova is still in outburst. This suggestion is supported by the presence of strong NV 1240Å. Some of the emission lines appear to be from FeII but more data could confirm or deny this possibility. This system is also very important because He II 4686Å is very strong and with both He II 1640Å and 4686Å present in the spectrum, an improved value of the reddening can be obtained.

7) **CP Pup (1942)** was one of the fastest novae on record and its light curve strongly resembled that of V1500 Cyg or some of the faster recurrent novae. The optical spectrum still shows strong He II 4686Å and the IUE spectrum (Figure 7) shows very strong He II 1640Å which implies that there is a hot source in the system. On the other hand, the continuum is flatter than in some other old novae and CIV is still very strong (NV 1240Å is a hit). It is important to obtain another IUE spectrum for this nova and see if NV 1240Å is present. The continuum has a very peculiar shape for an old nova. An abundance analysis of the emission lines could determine if the nova was still in outburst.

8) **V533 Her (1963)** is a nova for which data exist in the archives (Figure 8) but no spectrum has been obtained since 1980. Ten years is a significant fraction of the time since its

outburst and further data should show secular variations. The existing spectrum shows a blue continuum with strong CIV and He II. However, NV 1240 does not seem to be present which suggests that the emission is coming from an accretion disk and the nova has actually turned off.

9) **GQ Mus (1983)** has been observed with the IUE satellite since March 1983 so that a rather complete picture of the ultraviolet evolution of its outburst has been obtained. It was a moderately fast nova that was well studied at optical, IR, X-ray and radio wavelengths (see Ögelman, Krautter, and Beuermann 1987; Krautter and Williams 1989; and references therein). We obtained the most recent spectrum in September 1989 and it (Figure 9) shows a very blue continuum with strong He II 1640Å and OIII] 1660Å, 1666Å. This nova is definitely still in outburst and it was recently found that [FeX] was stronger than H α (Krautter and Williams 1989). The underlying object must be very hot. This nova will be studied with **ROSAT**.

10) **PW Vul (1984)** is a very slow nova that has recently been analyzed and shows solar He/H, C and O but nitrogen is 50 times solar (Saizar *et al.* 1990, and these proceedings). Solar He/H is very surprising (Truran and Livio 1986) and additional data is needed on the ultraviolet evolution of this nova. We are still obtaining optical data and we note that it was detected by **EXOSAT** (Ögelman, Krautter, and Beuermann 1987). The last IUE image, obtained in 1988 (Figure 10), was very underexposed. It is possible that a combined US1 + Vilspa exposure could provide improved S/N but, more likely, this nova should be studied with **HST**. This nova will be studied by **ROSAT**.

11) QU Vul (1984) was a "slow" ONeMg nova since its ultraviolet spectral evolution was very different from the other ONeMg novae in the archives (V693 CrA and LMC 1990 #1; Sonneborn *et al.* 1990; these proceedings). We obtained a 16 hour exposure (Figure 11) in September 1989. It is somewhat underexposed as compared to GQ Mus and any remaining ultraviolet spectra will have to be obtained with HST. He II 1640Å is present and [Ne IV] 1602Å and OIV] 1402Å may still be present.

12) Nova Oph (1988) is a nova for which no ultraviolet spectra were obtained. It never became bright enough to guarantee that we could study it for a reasonable length of time. However, it has been followed in the optical (Figure 12) and the latest optical spectrum is displayed here to show that the underlying object must be very hot. It also shows strong He II 4686Å plus a large number of coronal lines such as [Fe VI], [Fe VII], [Ca V], and [Ca VII]. Note that [O III] 4959Å and 5007Å are absent which also indicates that the shell is very hot. This nova should be studied by both ROSAT and HST.

III. SUMMARY AND DISCUSSION

We have presented spectra of some of the old novae that exist in the IUE Archives. It is clear that the archives contain observations of novae with a broad distribution in time since outburst and analysis of the existing data should ultimately provide useful estimates of the time that it takes a nova to turn-off. We are now in the process of trying to determine the appropriate spectral signatures of novae that are in outburst. We plan to use CLOUDY

(Ferland 1990) to obtain a consistent set of nebular line indicators in order to determine the characteristics of the central object and try to distinguish a hot white dwarf, which is still undergoing nuclear burning, from an accretion disk. We note that we can use the extensive set of observations of planetary nebula nuclei, for which the central stars have similar characteristics to novae in decline from maximum, to guide our analyses (Koppen and Wehrse 1983; Koppen and Aller 1987).

We are pleased to acknowledge partial support from NSF grant AST88-18215 to Arizona State University, NASA grant NAG 5-481 to Arizona State University, and to NSF grant AST 87-19607 to Ohio State University and to the DOE. We are also grateful to the staff of the Boulder RDAF which is supported by NASA grant: NAS5-28731 and to the IUE observatory which supported obtaining the data.

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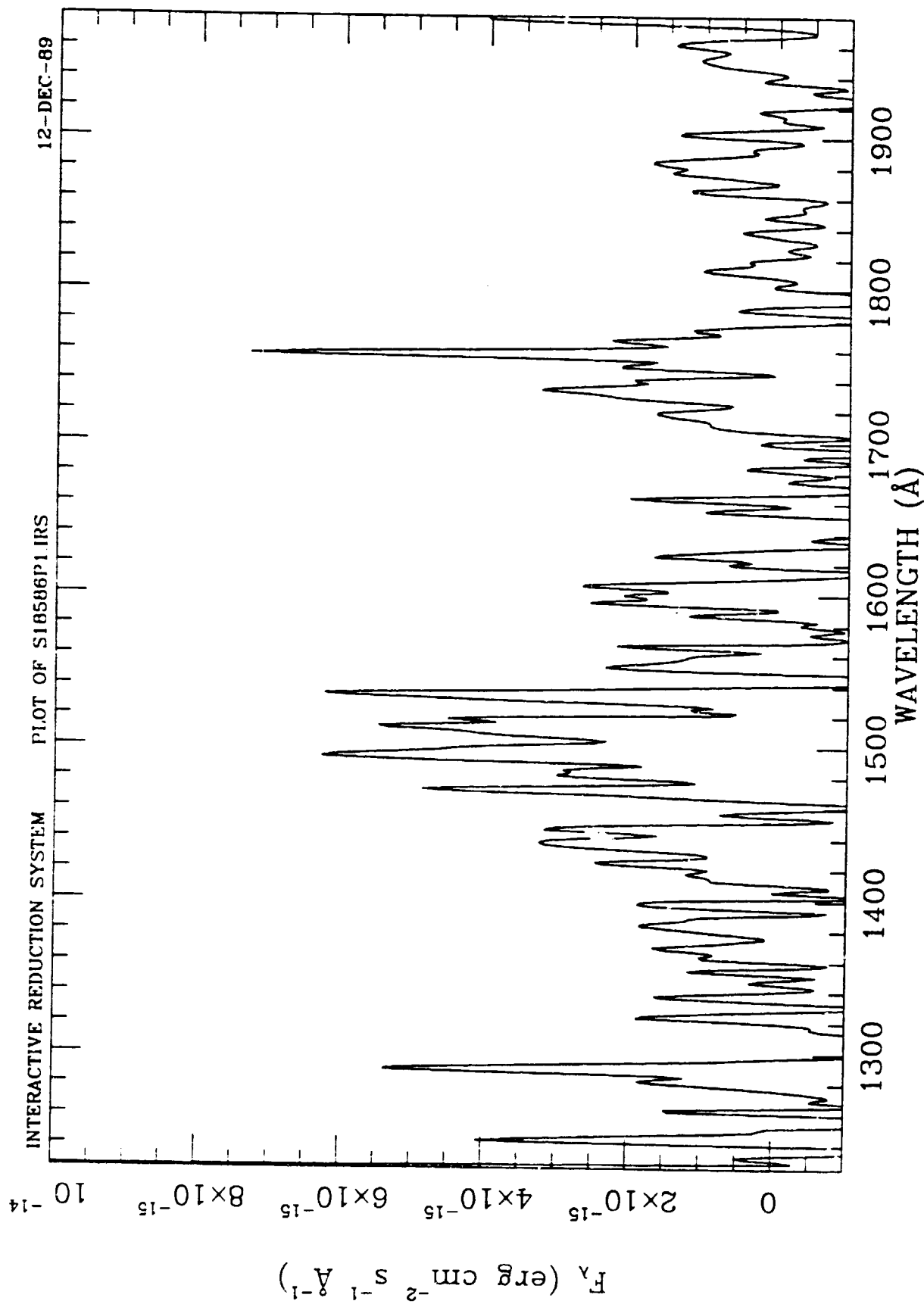
TABLE 1
SOME OF THE CLASSICAL NOVAE IN THE IUE ARCHIVES

NOVA	YEAR	MAG	A_V ²	Last Exp ³	SWP #
CK Vul	1670	~ 18.5	?	1982/322	18586
V841 Oph	1841	13.5	?	1980/45	07950
Q Cyg	1876	15.0	?	1989/2	35239
T Aur	1891	15.2	1.5	1983/319	21546
DI Lac	1910	14.9	<0.05	1986/271	29325
BT Mon	1939	15.4	<0.05	1986/48	27732
CP Pup	1942	15.0	0.3	1986/58	27806
V533 Her	1963	15.0	0.2	1980/273	10250
GQ Mus	1983	~ 15.5	~ 1.2	1989/245	36930
PW Vul	1984	~ 15.5	< 0.1	1988/175	33803
QU Vul	1984	~ 16.5	~ 1.5	1989/246	36933

¹Year of Outburst

²Obtained from Harrison and Gehrz (1988)

³Date of the last IUE spectrum



CK VUL (1670)

CAPTIONS FOR FIGURES

Figure 1. A 160 minute exposure of CK Vul on 1982/322 (322 is the day of the year in all of the figure captions).

Figure 2. A 120 minute exposure of V841 Oph obtained on 1980/45.

Figure 3. A 236 minute exposure of Q Cyg obtained on 1989/2.

Figure 4. A 90 minute exposure of T Aur obtained on 1983/219.

Figure 5. A 280 minute exposure of DI Lac obtained on 1986/271.

Figure 6. A 374 minute exposure of BT Mon obtained on 1986/48.

Figure 7. A 300 minute exposure of CP Pup obtained on 1986/58.

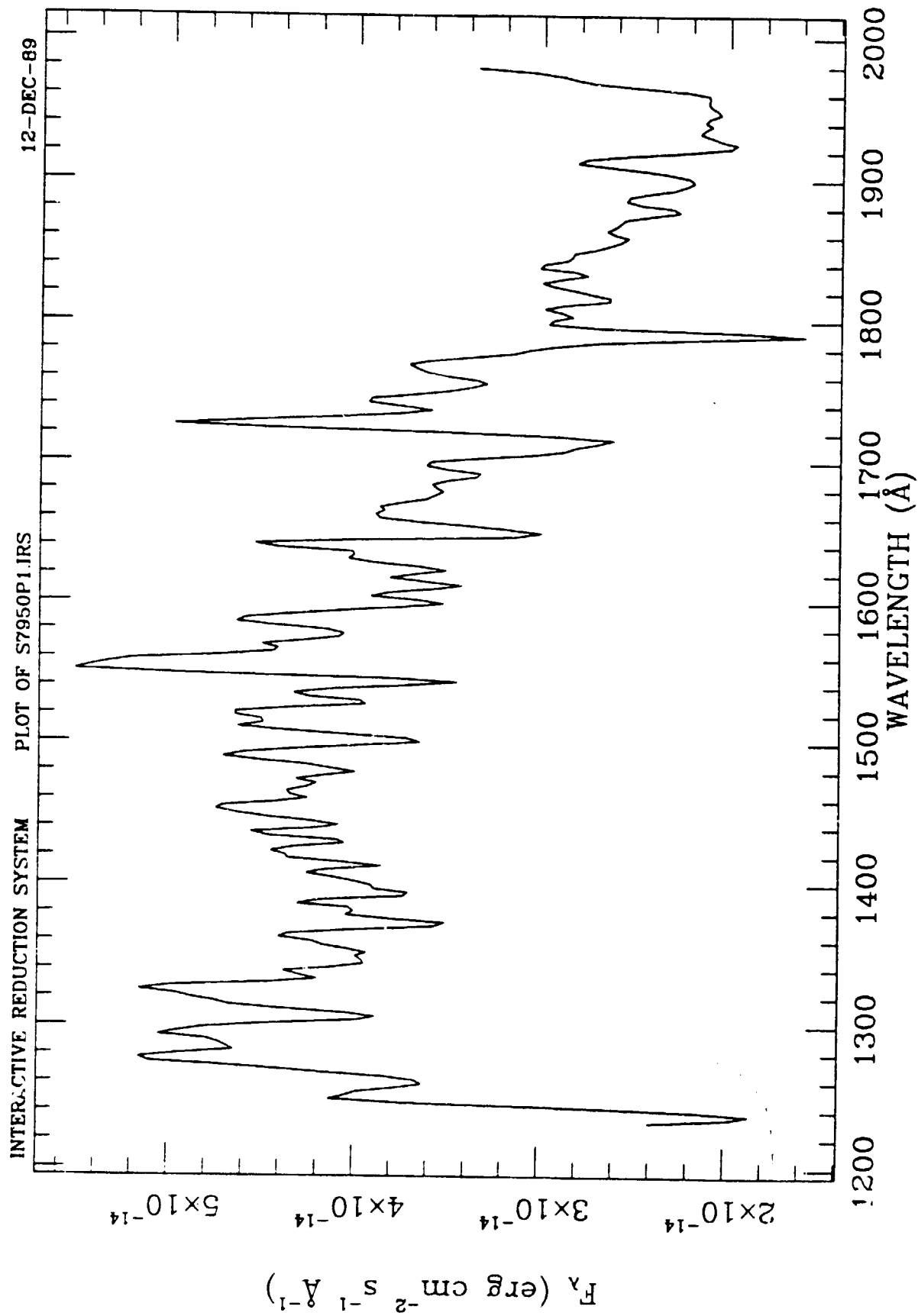
Figure 8. A 225 minute exposure of V533 Her obtained on 1980/273.

Figure 9. A 16 hour exposure of GQ Mus obtained on September 2, 1989.

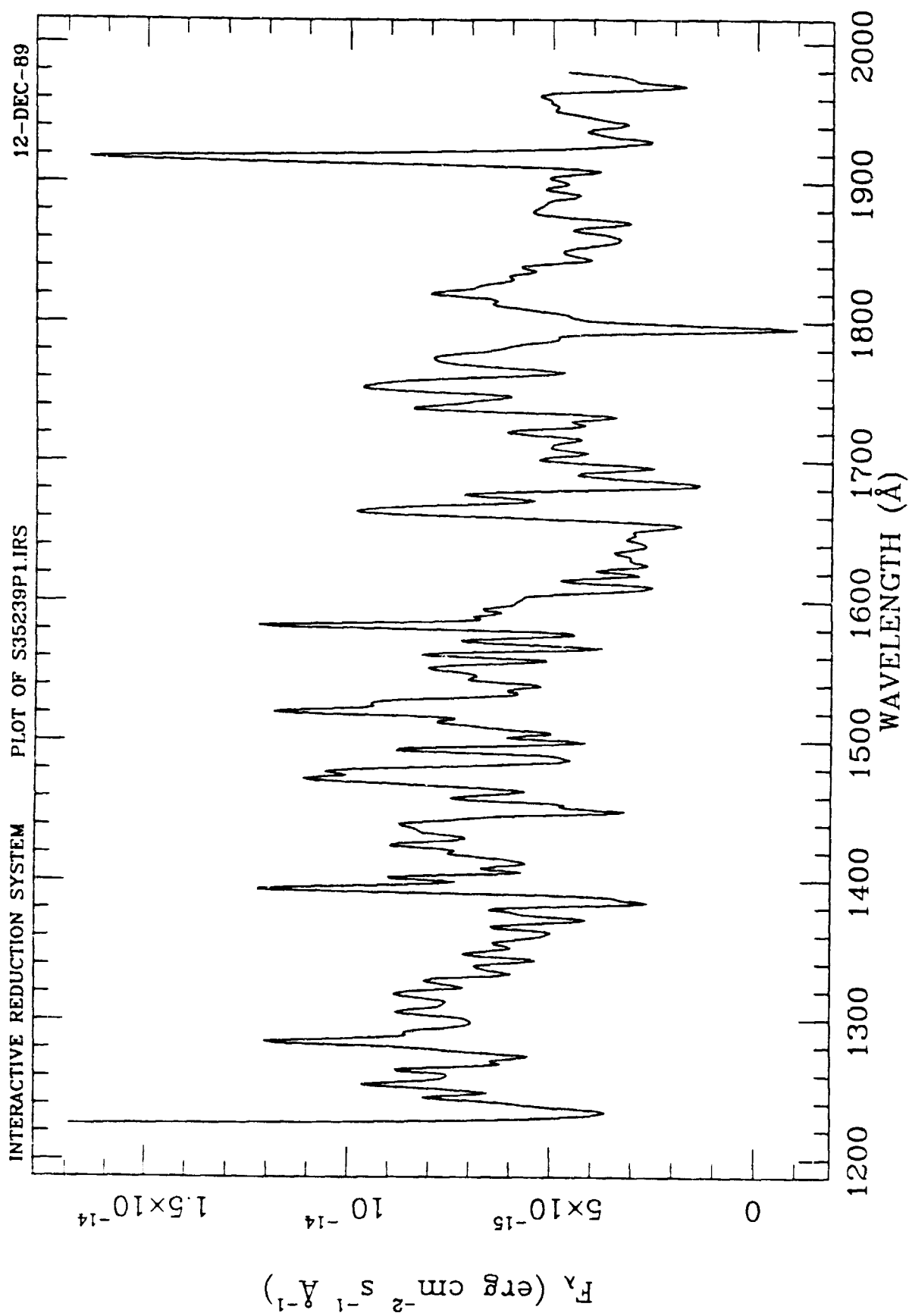
Figure 10. A 423 minute exposure of PW Vul obtained on 1988/175.

Figure 11. A 16 hour exposure of QU Vul obtained on September 3, 1989.

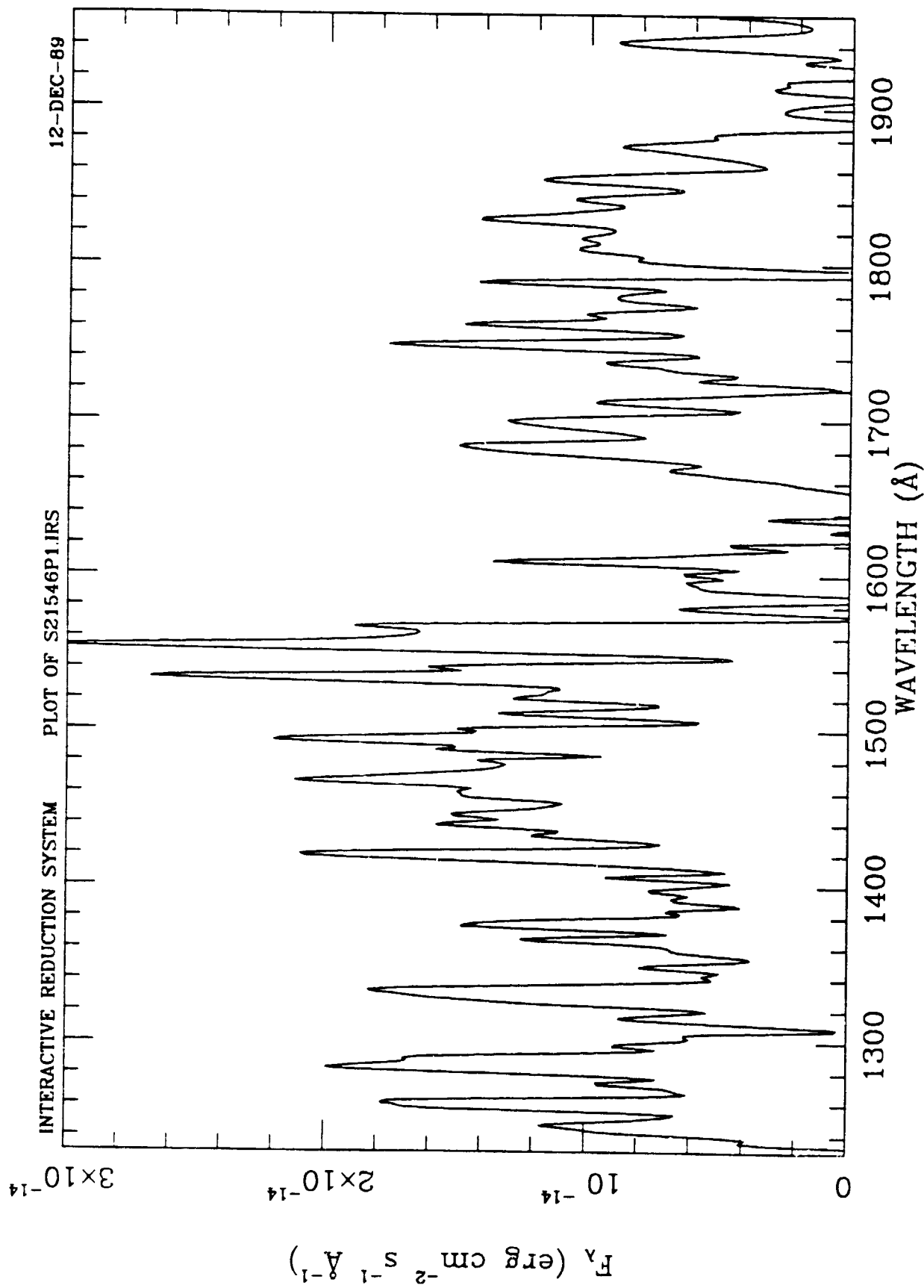
Figure 12. A 15 minute optical exposure of Nova Oph 1988 obtained on May 6, 1990 with the Perkins 1.8m telescope of the Ohio State and Ohio Wesleyan Universities. Note the strength of He II 4686 as compared to H β . Other lines are [Ca V] 5301Å, [Ca VII] 5612Å, and [Fe VII] 6085Å.



V B41 OPH (1841) (1481)



Q C Y G (1876)



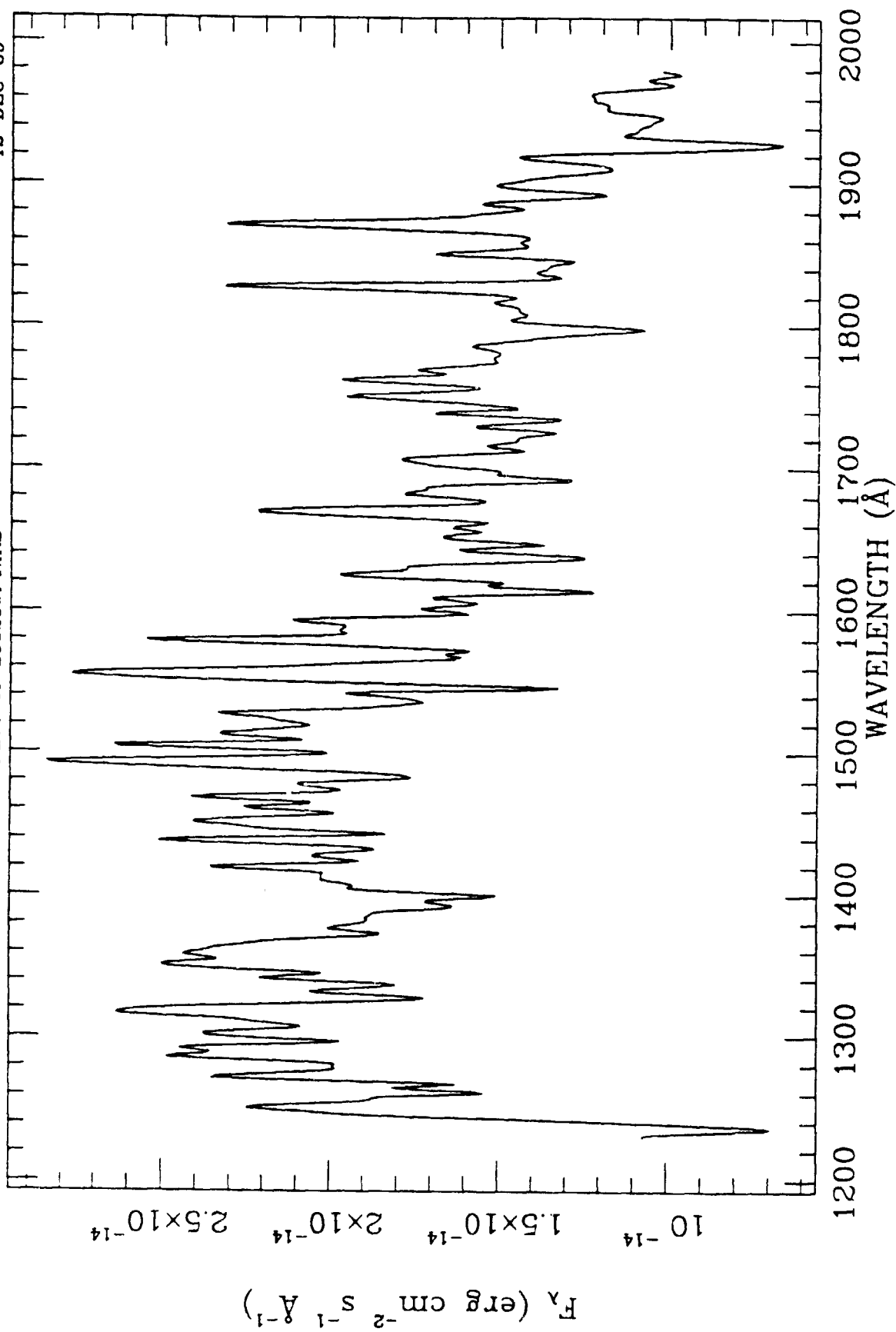
T AUR (1891)

24325

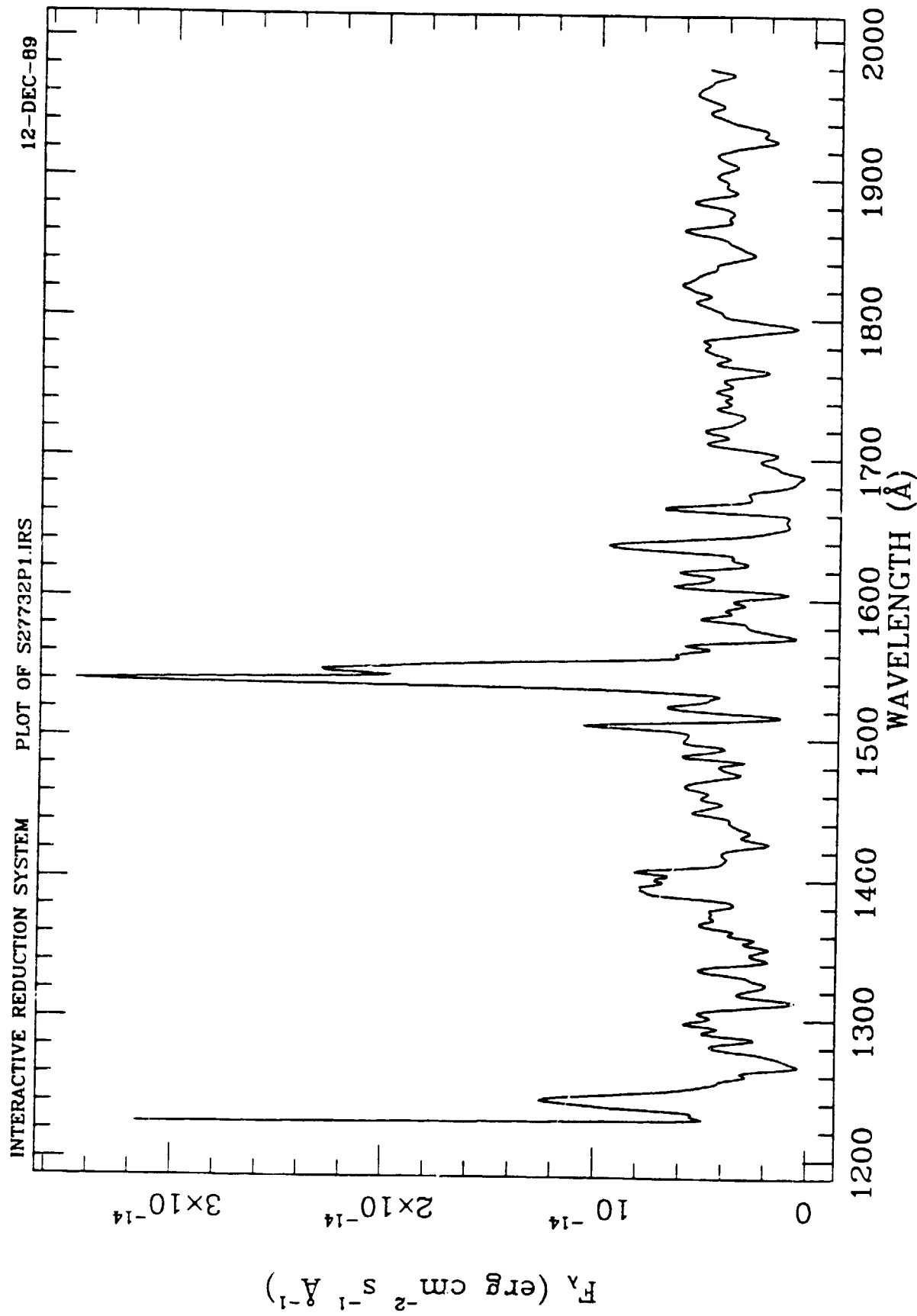
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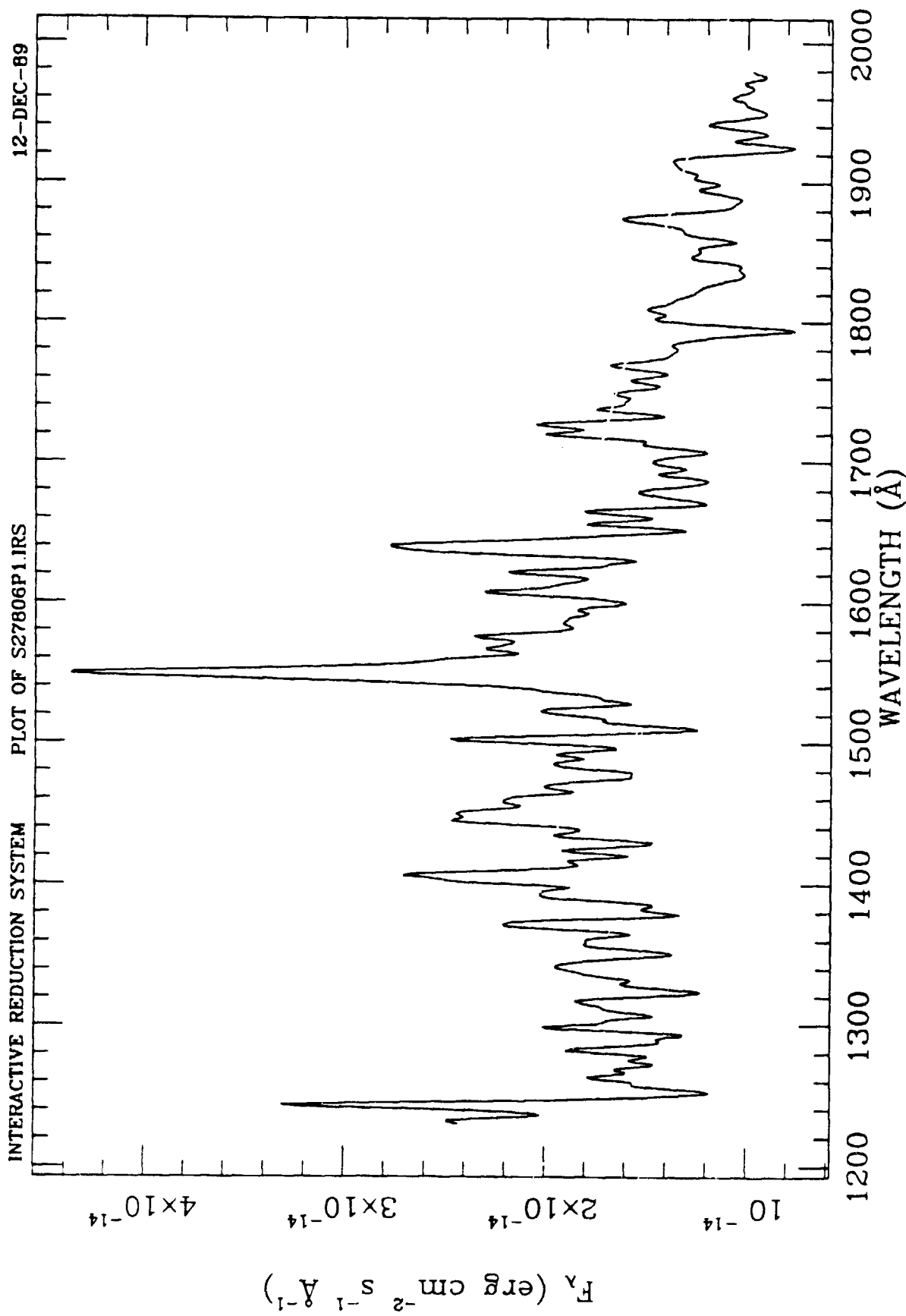
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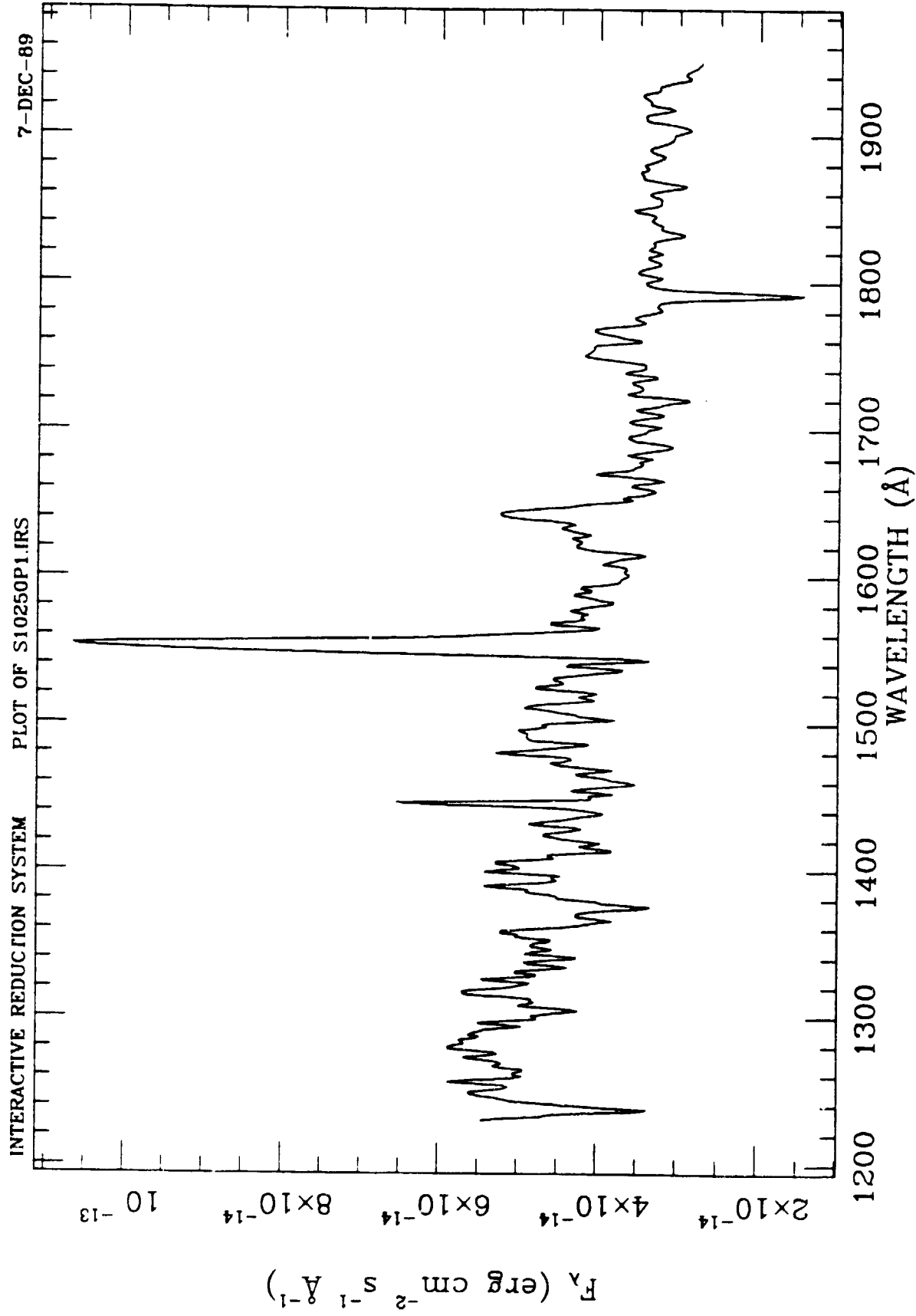
DI LAC (1910)



BT MON (1939)

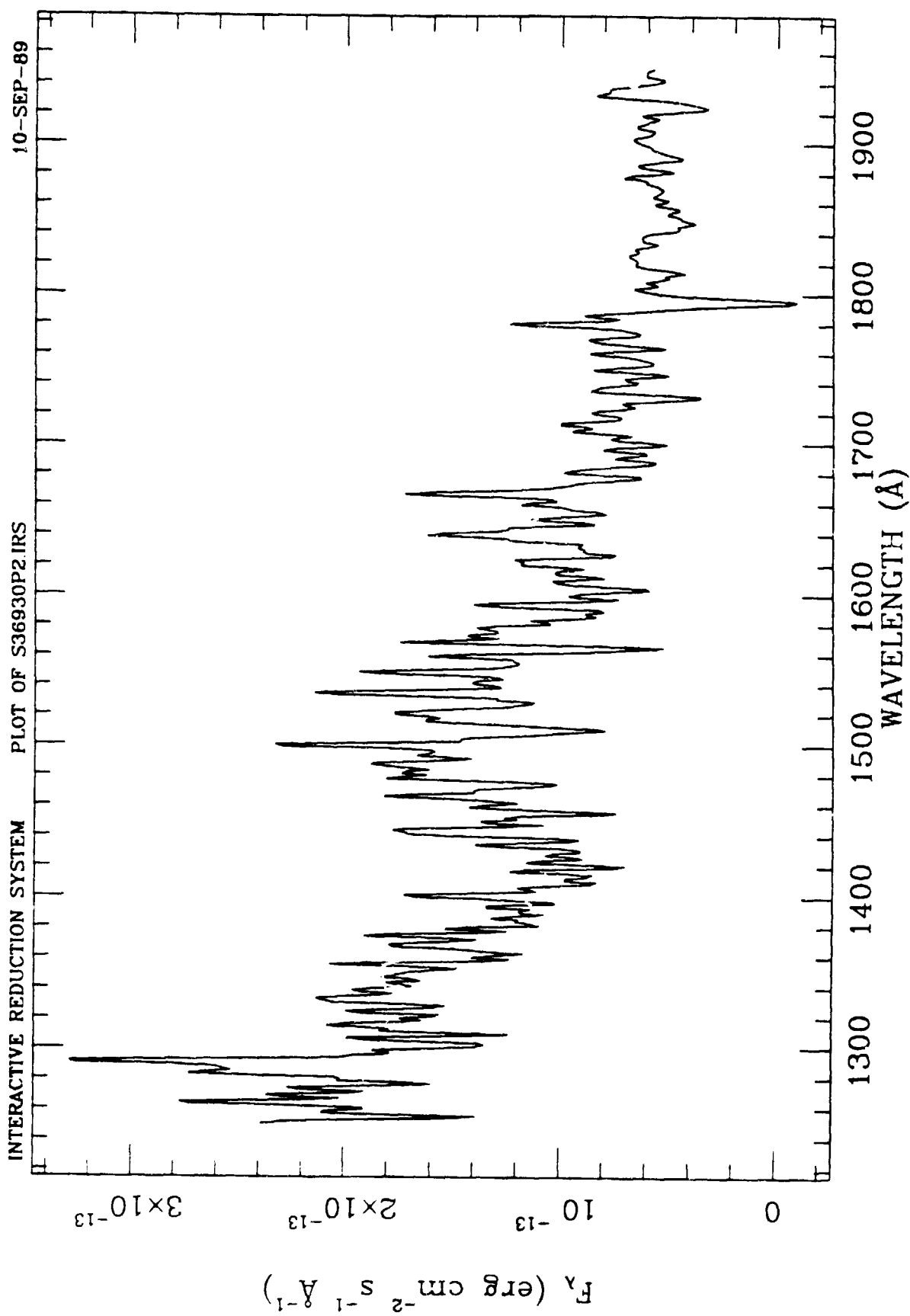


CP Pup (1942)

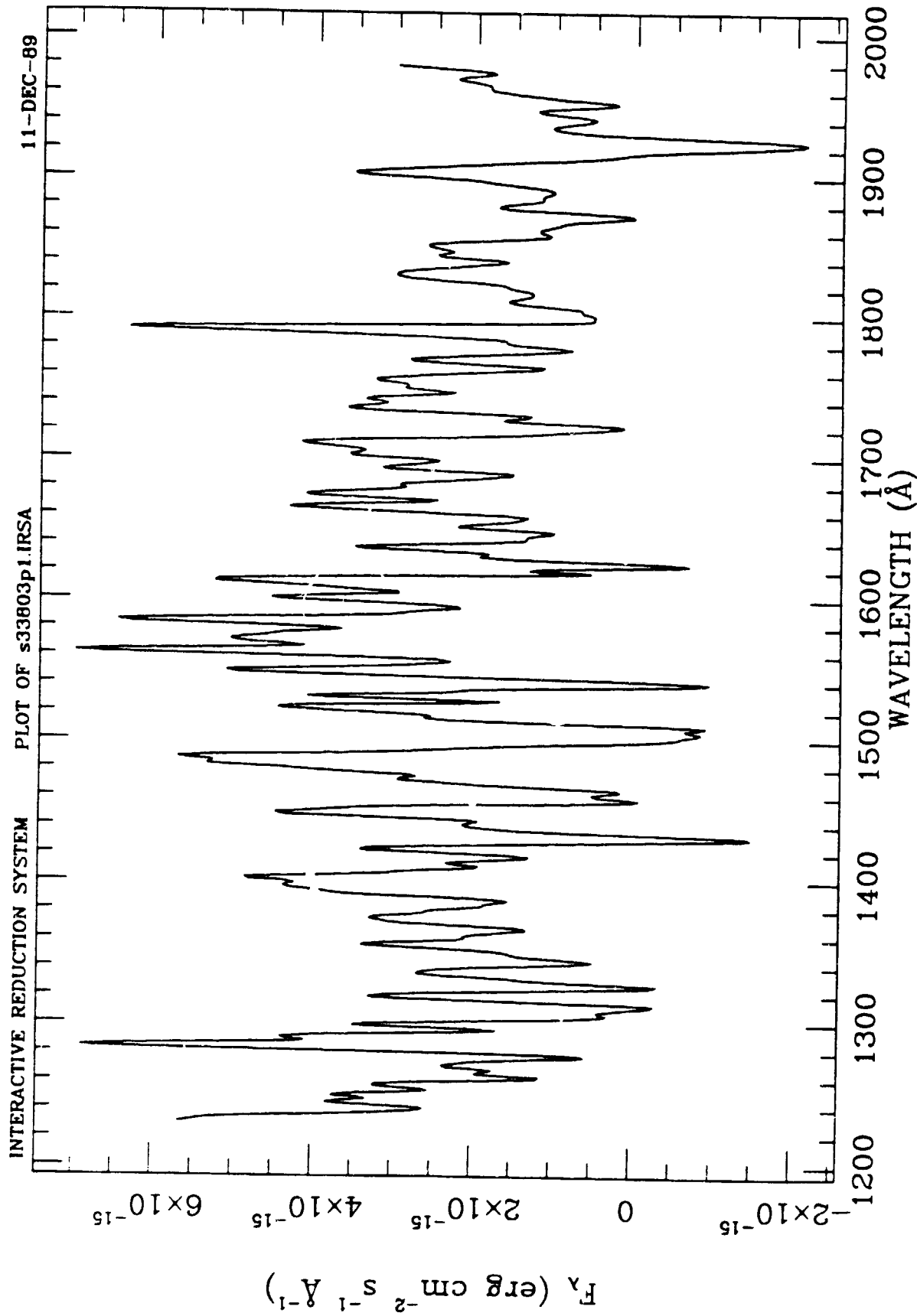


V533 Her (1963)

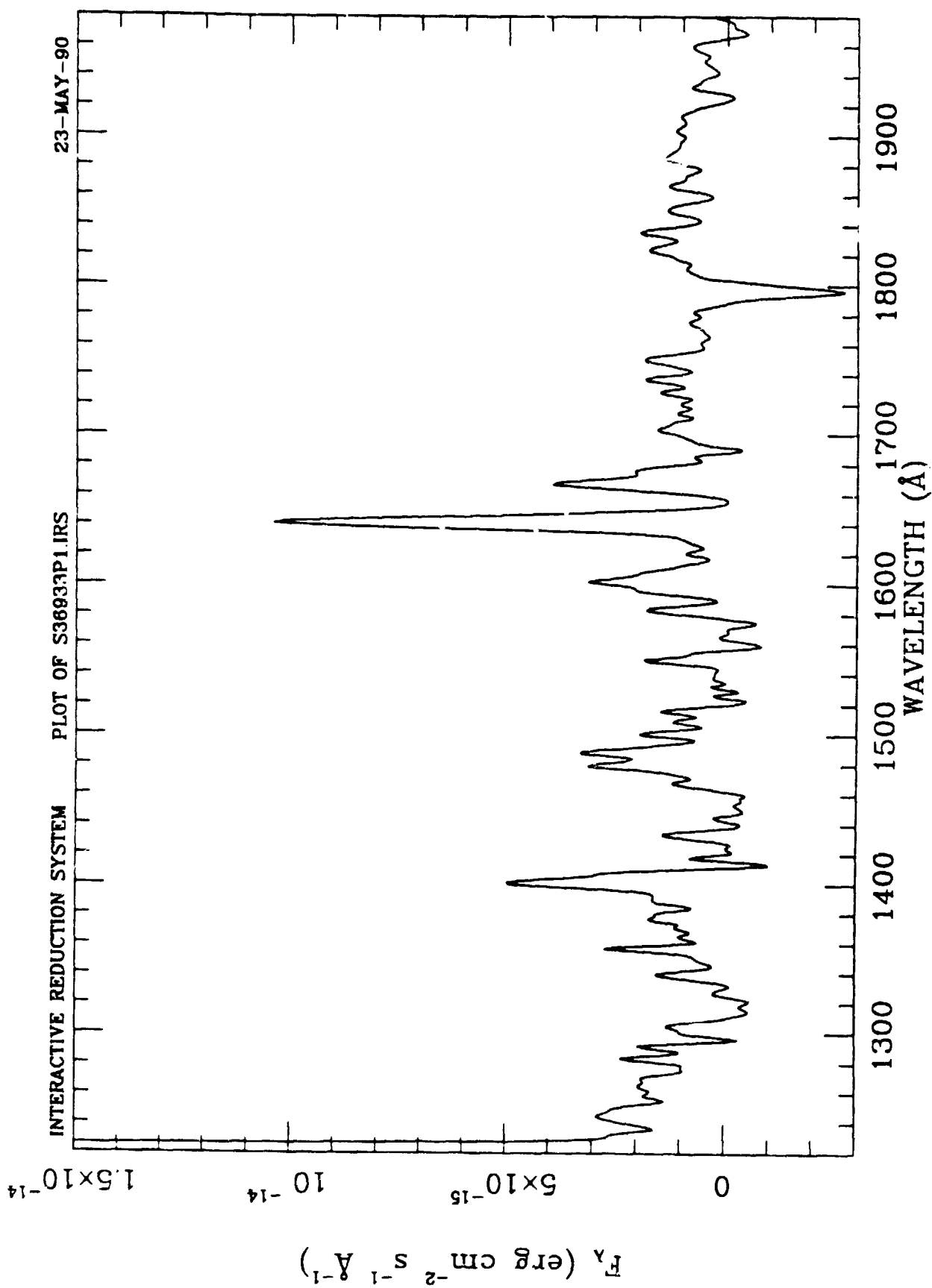
QJ 102 Sept 21/3 11



GQ MUS (1988)

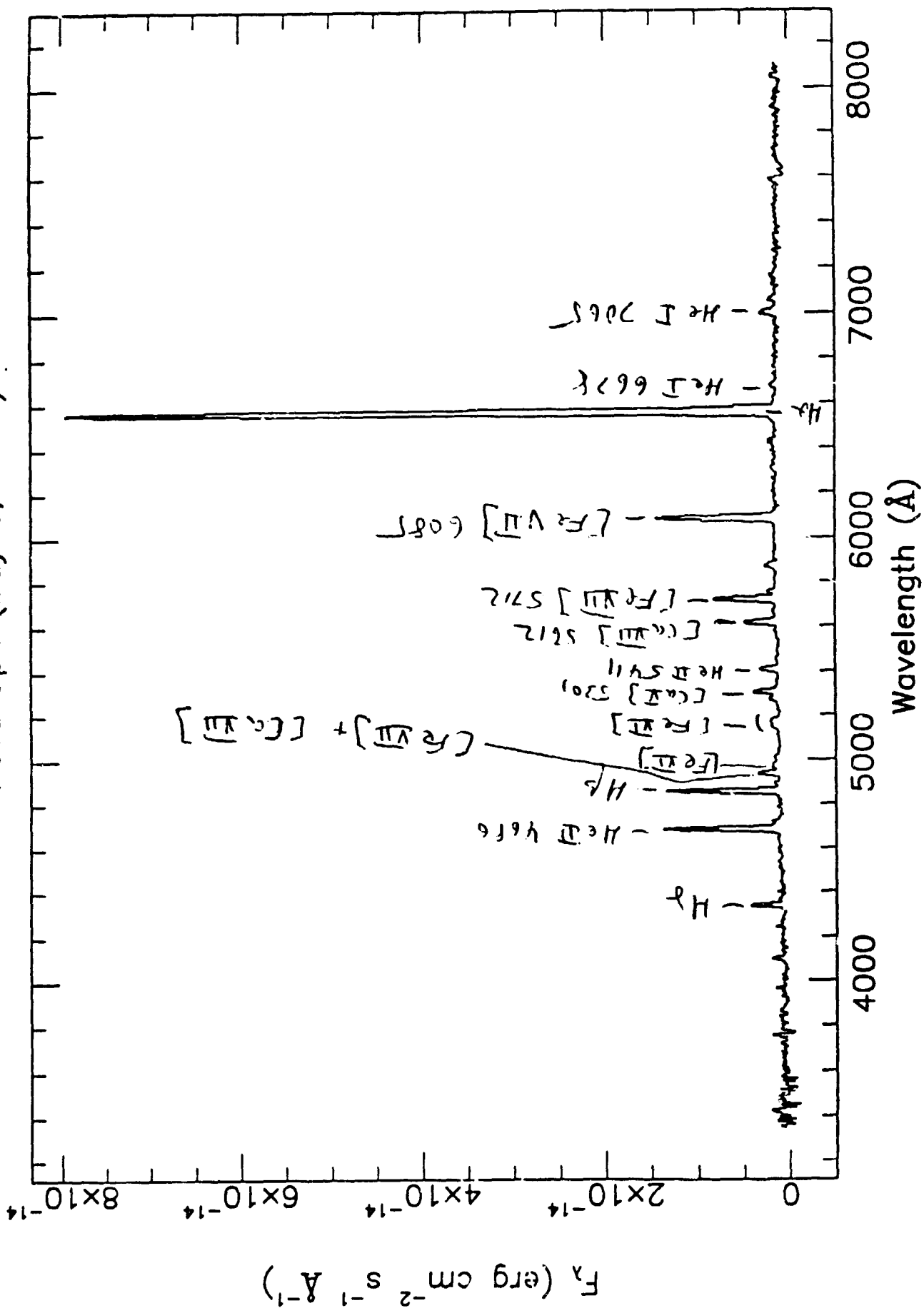


PW VUL (1984)



QU VV (1984)

Nova Oph (May 6, 1990)



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